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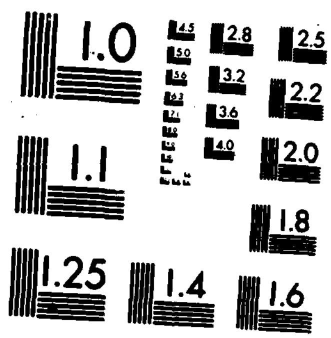

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Research on this contract gradually shifted from the treatment of transport in the inversion channel of a silicon MOSFET to the general treatment of hetero-interfaces and superlattices, as well as the use of the transport perpendicular to the interface to study the properties of the materials themselves. New understanding of the limitations of optical measurements of inter-band transitions in quantum wells in determining the band offsets were obtained.

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Final Report on

TRANSPORT IN SUBMICRON MOSFETS

September 15, 1986

For the Period

August 15, 1983 to August 14, 1986

DAAG29-83-K-0111

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Abstract

Research on this contract gradually shifted from the treatment of transport in the inversion channel of a silicon MOSFET to the general treatment of hetero-interfaces and superlattices, as well as the use of the transport perpendicular to the interface to study the properties of the materials themselves. New understanding of the limitations of optical measurements of inter-band transitions in quantum wells in determining the band offsets were obtained.

During the course of this research, quite a number of different projects were pursued. The results of these investigations are summarized below.

GATE FIELD INDUCED CARRIER HEATING IN Si MOSFETS

It is widely recognized that carriers moving near the $Si\text{-}SiO_2$ interface in MOSFETs exhibit a mobility that decreases with the transverse (gate) electric field, and that the dependence of the mobility on this field is described by the effective field

$$E_{eff} = e(N_s + N_{depl.})/2 \quad , \tag{1}$$

where N_s and $N_{depl.}$ are the inversion and depletion charge, respectively. The role of the effective field applies regardless of impurity concentration and substrate bias. Traditionally, it has been assumed that the reduction of mobility was associated with enhanced scattering at the oxide interface by, e.g., surface roughness scattering. However, at least one author has proposed that the mobility reduction is due in part to carrier heating by the gate field, a suggestion that has been properly criticized due to the fact that there is no net motion of the carriers, and hence no current flow in the direction transverse to the channel.

We measured the transverse electric field effect on transport in Si MOSFETs, both enhancement and depletion mode devices. The results of these measurements, in which the noise equivalent temperature of the channel carriers was measured, suggest that the carriers can be heated by the transverse gate field. It is found that the effective noise temperature increases with the square of the gate field, a dependence that strongly suggests the presence of carrier heating. These experiments were carried out on n-channel enhancement and depletion mode devices, in which a special gate structure was used with a Hall bridge structure under the gate. This allowed direct measurements of the Hall voltage in the channel for determination of the carrier density and mobility simultaneous with the noise measurement.

It is felt that terms in the energy stress tensor, normally ignored in carrier transport, are responsible for the heating. These terms allow for the presence of non-diagonal correlations between the momentum and the energy to appear, although these have always thought to be small. Such an effect would in principle couple the mobility degradation by the transverse field to the longitudinal energy and heating of the carriers.

THEORETICAL STUDY OF SUBBAND LEVELS IN SEMICONDUCTOR HETEROSTRUCTURES

We used an envelope-functionformalism, which is suited to the investigation of layered structures in semiconductors, to investigate a large class of weakly inhomogeneous heterostructures. Eight Γ-point Bloch functions to expand the wave functions of the confined states and included remote bands in second-order perturbation theory. The basis was chosen such that the spin-orbit interaction is diagonal for $k=0$. The eigenvalue problem becomes a system of coupled differential equations in the envelope functions. This system can be decoupled for the individual bands only if motion normal to the interfaces (in the z-direction) is studied and terms higher than second order in d/dz are neglected. This model was used to investigate single and multiple quantum wells consisting of thin slabs of GaAs and $Ga_{1-x}Al_xAs$. We calculated the subband levels for single quantum wells of varying thickness and alloy concentration and compared them to experiment. The influence of band offsets and effective masses, alloy concentration and layer thickness, and deviations from an ideal rectangular barrier were all examined.

No optimal values of band offset could be obtained consistently from any of the various experimental papers, since the energy levels of these structures show a significantly increased sensitivity to the choice of parameters. The levels are far more sensitive to slight variations in the well thickness than to the band offset, so that fabricational fluctuations significantly distort possible interpretation.

We then investigated the use of non-rectangular quantum wells as a basis for experimental investigation of band offsets. The use of triangular or 1/z barriers greatly reduces the sensitivity of the measurements to the exact well thickness, and thus makes the results more sensitive to the band offset.

ELECTRONIC PROPERTIES OF STRAINED-LAYER HETEROSTRUCTURES

For the majority of all combinations of semiconductors that are desirable for the fabrication of quantum well structures and superlattices, lattice mismatch will occur at the interface. This mismatch is due to the different lattice constants in the materials. It has been shown, however, that this misfit can be accommodated by uniform elastic strain if the layer thicknesses do not exceed critical, strain-dependent values. A k.p model was developed to describe the electronic structure of strained-layer quantum well structures and superlattices made from direct-gap III-V compounds. It was used to investigate strain effects for selected quantum well structures. The presence of strain modifies the electronic structure of the constituent layers and, consequently, influences the electronic properties of the heterostructure as a whole. In particular, the strain-induced shifts of the band edges are of the same order of magnitude as the band offsets at the interfaces. Based on theoretical models for the band offset that assume the existence of "characteristic" levels one can predict the band offsets as a function of intrinsic strain. Strong variations of the band offset parameter Q_e are obtained. This suggests that strain effects may be used as a tool for band-gap engineering. By growing a given quantum well structure lattice matched onto different substrates, different lattice constants can be imposed onto the structure. This allows one, to some extent, to choose how strain is distributed among individual layers. Using the k.p model, it could be shown that the optical properties of strained-layer heterostructures, such as interband transition energies, can be varied considerably by this technique.

TUNNELING IN THIN OXIDES

Inelastic Electron Tunneling Spectroscopy (IETS) is a way of studying the density of states in solids. If spectra can be measured, they can potentially be interpreted in ways which will substantially increase knowledge of the transport properties of materials. To expose some features of materials which are hidden under normal circumstances, strong magnetic fields must be applied.

In order to apply magnetic fields of up to nine tesla, the experiment under discussion makes use of a superconducting magnet which is located in a cryogenic dewar. Both the magnet and the sample to which IETS is being applied are to be exposed to temperatures on the order of just a few degrees Kelvin. A typical temperature is that of liquid helium--4.2 degrees. In order to achieve and maintain such low temperatures, a moderate vacuum is needed both as a thermal insulator and to create a flow of helium vapor across the sample. Such a vacuum system has been designed and the majority of its equipment has been installed.

Since it is desirable that any sample be held at a constant temperature, a computer can be used to monitor and control the temperature seen by the sample. A feedback system wherein a temperature sensor tells the computer of the sample's temperature and a heater is used to generate more helium vapor to flow by the sample is needed. Such a system has been planned and has almost been completed.

The first test of the complete experimental setup will be to tunnel electrons through heavily silicon doped gallium arsenide, a layer of silicon dioxide, and up to a metal contact. A strong magnetic field will be applied to expose silicon layers in the semiconductor. Most of the electronic test circuitry has been configured and installed.

HOT PHONONS IN QUANTUM WELL STRUCTURES

If charge carriers of a crystal are excited far out of equilibrium, carrier-phonon interaction may also cause the phonons to be driven out of equilibrium. Then, the "cooling capability" of the phonon bath will be reduced, and this, in turn, will have influence on the carrier dynamics. Such a situation is given if electron-hole pairs of high intensity are excited with a laser well above the band edges of a polar semiconductor. In this case, the dominant cooling mechanism is provided by LO phonon emission. It has been demonstrated that the heating of the LO phonon bath is predominantly responsible for the observed reduction in the cooling rates of the electron-hole gas in bulk GaAs.

Here, these investigations are extended to quantum-well structures made from GaAs and GaAlAs. Carriers confined in thin layers of GaAs exhibit (quasi-) 2D character. This may change the relative importance of phonon heating versus free-carrier screening. Sofar, we have developed the formalism to describe the carrier dynamics in quantum well structures. The electronic structure is obtained from a k.p model. The phonon dynamics is described by phonon Boltzmann equations for each phonon mode. At present, two different computational methods to study the time evolution of the laser-excited plasma are under investigation. One is an analytical approach similar to that used for bulk GaAs. This approach is tractable if simplifying assumptions are made about the system. Alternatively, the ensemble Monte Carlo method seems to provide a powerful tool to study effects of phonon heating without resorting to the simplifying assumptions needed in the analytical approach.

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